THE MASS AND HEAT BUDGET OF THE ANTARCTIC ATMOSPHERE

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ABSTRACT

Mean meridional wind components and eddy transports of sensible heat across 72°S. latitude are computed for each of six atmospheric levels from 850 to 100 mb., using 1958 data from 10 Antarctic stations. Mean vertical motions are obtained from the meridional wind components; a heat balance is struck for each of the six atmospheric layers, with radiational heat changes obtained as a residual. Results are compared with observed long-wave radiational cooling rates for the dark period (1962), and with results of other investigators.

For the entire Antarctic atmosphere between 950 and 75 mb., results showed downward vertical motions and loss of heat by radiational processes throughout the year. The heat thus lost to space is on the order of 10^{22} cal. Downward motion is at a maximum (about 0.35 cm./sec.) in the middle troposphere; heat is transported into Antarctica by horizontal eddies and by the mean meridional cellular circulation, and the relatively small difference between this heat inflow and the heat lost through radiation produces the observed temperature changes. The heat added to the Antarctic atmosphere from sensible heat transport and realized potential heat is one order of magnitude greater than that from condensation processes. The spring warming of the Antarctic stratosphere appears to result directly from dynamical processes of warm air advection and vertical sinking rather than from a direct gain of heat through radiation absorption, at least in the lower stratospheric levels treated here.

1. INTRODUCTION

The polar regions of the earth serve as the major "heat sinks" in the planetary thermal balance, with the earth's atmosphere acting as the principal medium by which the transfer of heat from low to high latitudes takes place. Although the geometrical and astronomical considerations governing the absorption of radiation are nearly identical for both hemispheres, the presence of an elevated continental mass covering most of the south polar region makes the Antarctic the most effective heat sink of our planet.

The establishment of an international network of radiosonde stations in Antarctica during the International Geophysical Year (IGY) of 1957–1958 made it possible to estimate with reasonable certainty the role of the Antarctic continent in the dynamics of the earth's atmosphere and in the planetary heat and water budgets. During the IGY, 18 upper-air sounding stations were operated on the continent, most of which made two ascents daily. Although ascents frequently reached the 50-mb. (about 20 km.) level in summer and occasionally during the winter, the highest level from which data are used in this investigation is the 100-mb. (about 15 km.) level.

One of the main aims of the U.S. Weather Bureau's Polar Meteorology Research Project (PMRP), supported by a National Science Foundation grant, is to describe and evaluate the mechanisms by which mass, heat, and water transports in and out of Antarctica are effected [7, 8, 9, 10]. Similar Northern Hemisphere studies have been carried out by other researchers [3, 4, 6, 11, 12], and the reasonably good data network has resulted in these efforts meeting some success. The present report describes the methods used by the PMRP in part of its program, which it is hoped will eventually result in a more complete and reliable description of all the atmospheric transport mechanisms, and their implications for the mass, heat, water, and energy budgets of Antarctica. Although Rubin [9] has reported on the meridional wind components for June and December 1958, using a similar station network, and for all months of 1958 for Mirny, his discussion was confined to the atmospheric circulation and its variations along the Antarctic periphery, with no attempt to obtain the heat transports which are our main concern here. In another paper, Rubin [10] made brief mention of the preliminary results of these computations, but the present investigation is based on a modified computational procedure and gives details of the contributions to the heat budget of various eddy terms as well as the variations of these terms seasonally. In this study we treat only 1958 data except for some 1962 radiometersonde data used for comparison.

2. METHODS

Most of the upper-air stations operating in the Antarctic are close to the coast, with only three stations near the central portion of the continent (fig. 1.). Because of the eccentricity of the continental mass with respect to the geographic pole, the circle of best fit for the ten peripheral stations used in this study (termini of radial lines, fig.1) is a circle centered at 83° S., 90° E. with a radius of 17°58′ of latitude. True meridional wind components are

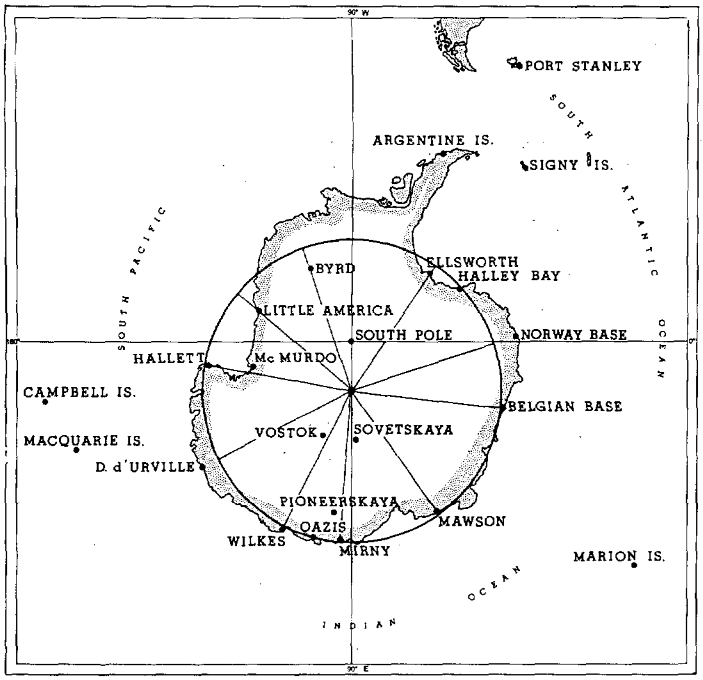

FIGURE 1.—Antarctic and other Southern Hemisphere radiosonde and rawinsonde stations in relation to circle of best fit for continental peripheral stations.

TABLE 1.—*Mean meridional wind components (m./sec.)—1958. Positive values from south*

		850 mb.	700 mb.	500 mb.	300 mb.	200 mb.	100 mb.
Jan.	10 sta.	0.82	0.34	−0.47	−0.41	−0.20	−0.33
	9 sta.	.93	.36	−.43	−.40	−.35	−.58
Feb.	10 sta.	1.83	.43	−.86	−.37	−1.10	−.80
	9 sta.	1.59	.14	−.85	.20	−.95	−.88
March	10 sta.	1.43	.27	−.62	−1.39	−.04	.50
	9 sta.	1.34	.14	−.50	−1.27	−.03	.53
Apr.	10 sta.	1.26	.55	−.19	−1.20	−.59	−.54
	9 sta.	1.03	.58	−.29	−1.03	−.39	−.40
May	10 sta.	2.43	.91	−.67	−1.89	−1.07	−.79
	9 sta.	2.13	.59	−.63	−1.40	−.91	−.67
June	10 sta.	1.36	.35	−.46	−.57	−.30	−1.23
	9 sta.	1.35	.31	−.58	−.47	−.36	−.96
July	10 sta.	.97	.30	−.71	−.70	−.28	.70
	9 sta.	.60	.30	−.53	−.62	−.40	1.07
Aug.	10 sta.	.95	.14	−.12	−.64	−.17	−.73
	9 sta.	1.15	.20	−.17	−.79	−.22	−.81
Sept.	10 sta.	1.85	.46	−.47	−1.54	−.51	−.37
	9 sta.	1.57	.19	−.47	−1.36	−.17	.09
Oct.	10 sta.	1.33	.23	−.29	−.26	−.96	−1.05
	9 sta.	1.41	.26	−.23	−.19	−1.03	−1.49
Nov.	10 sta.	1.16	.41	.10	−.64	−.87	−1.50
	9 sta.	1.17	.28	.17	−.36	−.85	−1.98
Dec.	10 sta.	.90	.52	−.47	−.63	−.32	−.38
	9 sta.	1.01	.45	−.70	−.63	−.23	−.37
Jan.–Mar. and Oct.–Dec.	10 sta.	1.25	.37	−.44	−.62	−.58	−.59
	9 sta.	1.24	.28	−.44	−.44	−.59	−.80
	Obasi	.84	−.16	−.28	−.34	−.05	−.13
Apr.–Sept.	10 sta.	1.47	.45	−.44	−1.09	−.49	−.49
	9 sta.	1.31	.36	−.45	−.95	−.41	−.28
	Obasi	.48	.12	−.40	−.12	+.11	−.24
Year	10 sta.	1.36	.41	−.44	−.86	−.54	−.54
	9 sta.	1.28	.32	−.44	−.70	−.50	−.54
	Obasi	.66	−.02	−.34	−.23	+.03	−.19
Oct. and Nov.	10 sta.	1.25	.32	−.10	−.45	−.92	−1.28
	9 sta.	1.29	.27	−.03	−.28	−.96	−1.74

used in this study, which is equivalent to assuming that each of the stations is representative of conditions at its own longitude at about 72° latitude. The atmospheric levels used are at 850, 700, 500, 300, 200, and 100 mb.; the temperature and the meridional wind components were determined at these levels for each radiosonde ascent. Because of the low temperatures only limited humidity data were available, so that the water vapor transports were not treated directly. The transports of mass and sensible heat were obtained as described in the Appendix, which also details some of the further computational procedures.

3. THE MASS BALANCE AND THE MERIDIONAL CIRCULATION

Mean meridional wind components, $\bar{v}$, were computed for each month of 1958 for each of the six levels, using all ten stations' data. In order to get some idea of how much these values would be changed if there were fewer or different data as is the case for later years, the computations were repeated after eliminating the Little America data and using only the other nine stations (Little America was closed in December 1958). Obasi [5] has calculated the mean meridional winds at various southern latitudes, using 1958 data, as part of a study of momentum and energy transports, and his values for 70° S., adjusted to fit our vertical partitioning of the atmosphere, were examined for further comparison. The mean meridional wind components, including both our ten-station and nine-station values and the Obasi values for two 6-month periods and the year, are listed in table 1.

Our results show a rather consistent pattern from month to month throughout the year, with inflow of air in the stratosphere and upper troposphere and a compensating outflow in the lower troposphere. This tropospheric circulation fits that postulated by Wexler et al. [13] to explain the transport of ozone into the Antarctic troposphere. His model showed influx in the upper troposphere, sinking through the middle troposphere, and outflow in the lower atmospheric layers, with the ozone entering the upper troposphere through the tropopause break in middle latitudes, and with only slight sinking from the stratosphere downward through the troposphere over Antarctica. With nine stations, the same general pattern holds true, although the absolute values change somewhat. Comparison of the ten-station and nine-station values suggests that, at least on an annual and seasonal basis, the elimination of one station's data would not change the sign or the order of magnitude of the computed meridional components. The vertical profile of mean meridional motions which emerges requires downward vertical motions throughout the depth of the atmosphere considered, both in the winter and in the summer. Obasi's results, although also requiring downward vertical motion in both the stratosphere and troposphere, suggest separate tropospheric and stratospheric meridional cells, with little interchange through the tropopause level (between 300 and 200 mb. on the average).

Assuming that the computed $\bar{v}$ for each level is representative of the layer of air containing this level, we can compute both the mass transports for each layer and the vertical velocities necessary to achieve a mass balance (assuming zero flow through the 75-mb. level and through the 950-mb. level, the quasi-horizontal boundaries of the

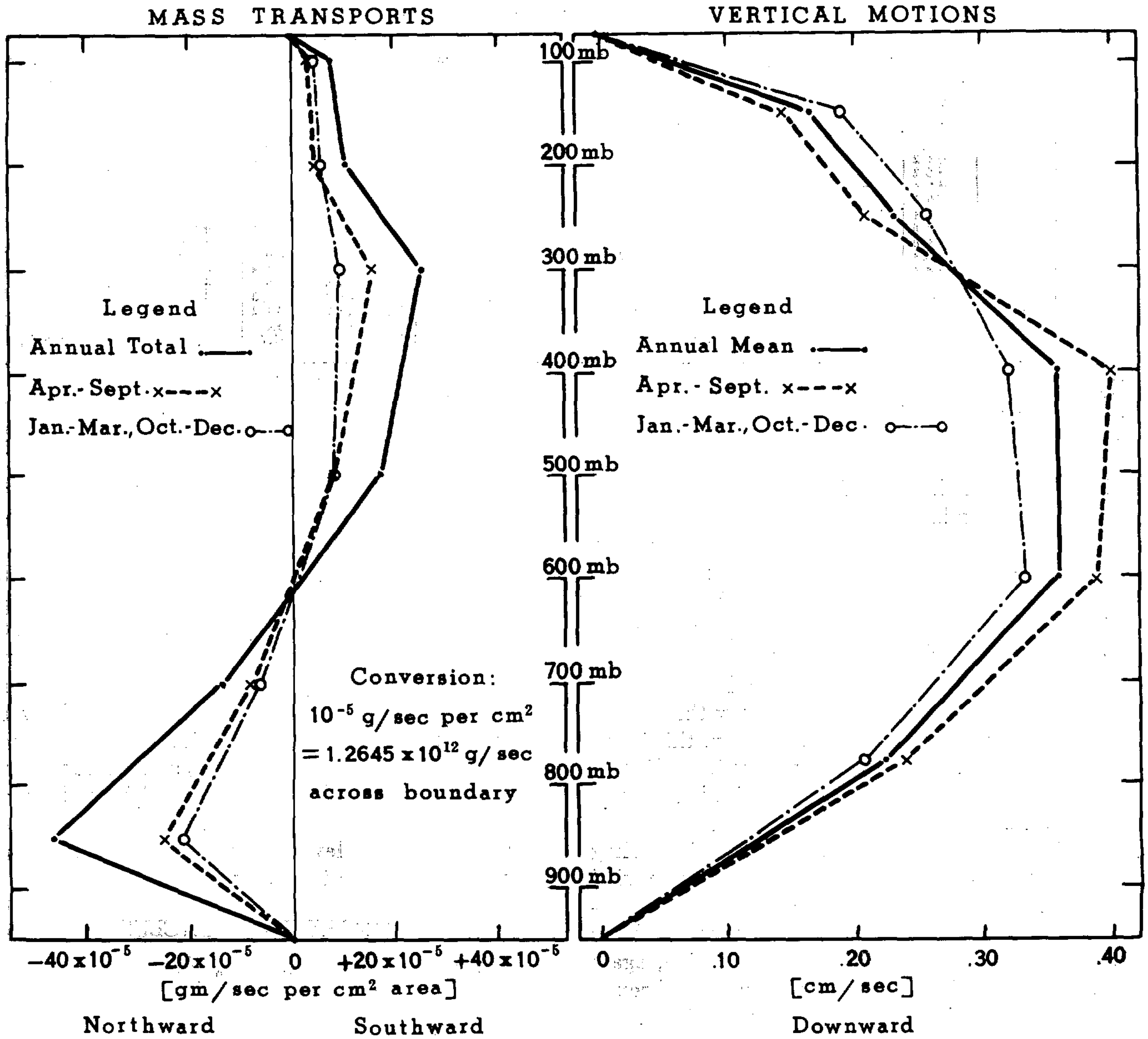

FIGURE 2.—Mean mass transports and vertical motions in the Antarctic atmosphere, 1958.

portion of the atmosphere we are considering here). Results of these calculations for the year and for two 6-month seasons are shown graphically in figure 2. The layer of near zero net horizontal transport, about 600 mb., is also the lower boundary of the region of maximum downward vertical motion, which averages about 0.36 cm./sec. over the whole year in this layer.

4. HEAT BALANCE AND ATMOSPHERIC COOLING RATES

We have computed the horizontal sensible heat transport resulting from large-scale transient eddies and from standing eddies. Disregarding, for the time being, any net latent heat transport and the turbulent exchange of heat between the atmosphere and the snow, we can now attempt a heat budget for each of our layers of the atmosphere and for the entire atmosphere from 950 mb. to 75 mb. By summing the gains or losses of heat through horizontal eddy transports, through release of heat from downward vertical motions, and through the observed temperature changes within the layer, we can (neglecting latent heat and condensation) arrive at the heat loss through radiational processes required to produce a heat balance for each atmospheric layer (table 2).

The overall annual heat loss through radiation from the atmosphere between 950 and 75 mb. for our Antarctic area (12.645×10^{16} cm.^{2}) is about 1.4×10^{22} cal. (303 ly./day). This is the equivalent of about 1.5×10^{22} cal. for the total Antarctic area (13.48×10^{16} cm.^{2}) used in other investigations [10]. If we take the total precipitation as being 11 to 17 cm. of water annually [10], an additional 0.1×10^{22} cal. of heat is added to the atmosphere giving a

TABLE 2.—*Components of Antarctic atmospheric heat budget and corresponding heating rates*

		75–150 Mb.		150–250 Mb.		250–400 Mb.		400–600 Mb.		600–775 Mb.		775–950 Mb.		75–950 Mb.	
		ΔQ	ΔT	ΔQ	ΔT	ΔQ	ΔT	ΔQ	ΔT	ΔQ	ΔT	ΔQ	ΔT	ΔQ	ΔT
	E_s	+0.5	+0.1	+0.7	+0.1	+0.1	+0	+0.2	+0	+0.3	+0	+0.4	+0	+2.2	+0
	E_t	+4.2	+1.0	+1.4	+0.3	−0.1	−0	+1.4	+0.1	+1.2	+0.2	+1.3	+0.2	+ 9.4	+0.2
Jan.–Mar. and Oct.–Dec.	Q_θ	+6.2	+1.5	+14.4	+2.6	+11.0	+1.3	+10.5	+0.9	+9.6	+1.0	+3.5	+0.4	+55.2	+1.1
	Ob.	+0.4	+0.1	+0.6	+0.1	+0.2	+0	+0.3	+0	+0.2	+0	+0.3	+0	+2.0	+0
	R	−10.5	−2.5	−15.9	−2.9	−10.8	−1.3	−11.8	−1.0	−11.0	−1.1	−4.9	−0.5	−64.9	−1.3
	E_s	+0.4	+0.1	+0.3	+0.1	−0.2	−0	−.7	−0.1	+0.3	+0	+0.6	+0.1	+0.7	+0
	E_t	+3.6	+0.9	+1.3	+0.2	±0.0	±0	+.8	+0.1	+3.5	+0.4	+5.0	+0.5	+14.2	+0.3
Apr.–Sept.	Q_θ	+4.0	+1.0	+7.6	+1.4	+13.0	+1.6	+14.0	+1.3	+13.6	+1.4	+2.8	+0.3	+55.0	+1.1
	Ob.	−0.4	−0.1	−0.6	−0.1	−0.2	−0	−0.3	−0	−0.2	−0	−0.3	−0	−2.0	−0
	R	−8.4	−2.0	−9.8	−1.8	−13.0	−1.6	−14.4	−1.3	−17.6	−1.8	−8.7	−0.9	−71.9	−1.5
	E_s	+0.9	+0.1	+1.0	+0.1	−0.1	−0	−0.5	−0.1	+0.6	+0	+1.0	+0.1	+2.9	+0
	E_t	+7.8	+0.9	+2.7	+0.3	−0.1	−0	+2.2	+0.1	+4.7	+0.3	+6.3	+0.3	+23.6	+0.2
Year	Q_θ	+10.2	+1.2	+22.0	+2.0	+24.0	+1.4	+24.5	+1.1	+23.2	+1.2	+6.3	+0.3	+110.2	+1.1
	Ob.	±0	±0	±0	±0	±0	±0	±0	±0	±0	±0	±0	±0	±0	±0
	R	−18.9	−2.2	−25.7	−2.4	−23.8	−1.4	−26.2	−1.1	−28.6	−1.5	−13.5	−0.7	−136.7	−1.4

ΔQ—Net gain of heat in 10^{20} cal.
ΔT—Heating rate in °C./day.
E_s—Contribution of standing horizontal eddies.
E_t—Contribution of transient horizontal eddies.
Q_θ—Contribution from realization of potential heat thru vertical sinking.
Ob.—Observed changes.
R—Contribution of radiational processes (a residual).

total radiative loss for the area of 1.6×10^{22} cal./yr. This latter figure corresponds to about 1.8×10^{22} cal. for the area within 70° S., about 10 to 15 percent higher than Gabites' [1] estimate of the total poleward heat flux across 70° S., and 15 to 25 percent higher than the estimates of Rubin [10]. Hanson and Rubin [2] have computed the loss of heat by the atmosphere to the snow through turbulent exchange of sensible and latent heat at the South Pole as averaging about 35 ly./day throughout the year; although neglected in this discussion, this is the equivalent of about 1.7×10^{21} cal. annually if applied to the total Antarctic area, one order of magnitude less than the total annual heat loss we have calculated.

A comparison of the computed atmospheric cooling rates for April to September 1958 with 1962 dark period radiometersonde data (about 180 ascents) from five stations (table 3) indicates that our computed stratospheric and upper tropospheric cooling rates are too high, again lending support to the idea of less vertical motion through the tropopause level than our computations indicate.

5. THE SPRING STRATOSPHERIC WARMING

In 1958, as in most years so far observed in the Antarctic, stratospheric temperatures showed their greatest increase during the months of October and November (fig. 3). Accordingly, the 2-month period of October and November 1958 was examined separately, in order to assess the relative contributions of horizontal advection, vertical motion, and radiative temperature changes to the observed warming. The computed meridional components are included at the bottom of table 1; the inflow indicated at 100 mb. is considerably higher during this period than in any other 2-month period during the year. The results of our computations for this warming period are shown in table 4.

TABLE 3.—*Comparison of computed and observed radiational cooling rates (°C./day)*

	75–150 mb.	150–250 mb.	250–400 mb.	400–600 mb.	600–775 mb.	775–950 mb.	Mean
Computed	−2.0	−1.8	−1.6	−1.3	−1.8	−0.9	−1.5
1962 observed	−0.6	−0.1	−0.4	−0.9	−1.1	−1.2	−0.8

Although the actual warming of the stratosphere is at a maximum during October and November, the heating rate in the 75–150-mb. layer is still only 0.4° C./day during this period. The warming of the air through horizontal advection of sensible heat is about on the same order as the warming from net downward vertical motion, and each of these quantities by itself more than accounts for the observed warming, so that our computations still indicate radiational losses of heat during this 2-month period. It thus appears that, at least in these lower stratospheric levels, dynamical processes are directly responsible for the observed warming.

6. SUMMARY AND CONCLUSIONS

Using data for 1958 from ten Antarctic stations, the net transport of mass and of heat across the boundary of the area encompassed by these stations has been computed. There are some indications that the computed meridional components of the wind may contain appreciable error, particularly at stratospheric levels, with this error propagated to the computed vertical motions and to the residual radiational cooling rates. Possible sources of such error may be (1) the geometric assumptions made, (2) the limited vertical resolution of the data, (3) observational error, (4) chance errors due to a limited data sample, and (5) truncation of the part of the atmosphere above 75 and below 950 mb. No rigid analysis of error has been attempted, nor indeed is it practical to attempt such an analysis in view of the uncertainties involved. However, the rather good agreement as to the signs and magnitudes of the various computed quantities from month to month throughout the year indicates that our results are useful in a qualitative sense at least, as regards the algebraic sign and the general order of magnitude of the various quantities computed. With the above limitations in mind, we may list the following conclusions based on the computed results:

TABLE 4.—*Components of heat balance and corresponding heating rates: October and November*

	75–150 Mb.		150–250 Mb.		250–400 Mb.		400–600 Mb.		600–775 Mb.		775–950 Mb.		75–950 Mb.	
	ΔQ	ΔT	ΔQ	ΔT	ΔQ	ΔT	ΔQ	ΔT	ΔQ	ΔT	ΔQ	ΔT	ΔQ	ΔT
E_s	+0.3	+0.2	+0.4	+0.2	+0.2	+0.1	+0.2	+0.1	+0.1	+0	+0.3	+0.1	+1.5	+0.1
E_t	+3.6	+2.6	+0.8	+0.4	−0.3	−0.1	−0	−0	+0.2	+0.1	+0.4	+0.1	+4.7	+0.3
Q_t	+4.5	+3.2	+7.6	+3.8	+6.0	+2.2	+4.1	+1.1	+3.5	+1.1	+1.3	+0.4	+27.0	+1.7
Ob.	+0.6	+0.4	+0.4	+0.2	+0.3	+0.1	+0.4	+0.1	+0.3	+0.1	+0.3	+0.1	+2.3	+0.1
R	−7.8	−5.6	−8.4	−4.1	−5.6	−2.0	−3.9	−1.1	−3.5	−1.1	−1.7	−0.5	−30.9	−1.8

ΔQ—Net gain of heat in 10^{20} cal.
ΔT—Heating rate in °C./day.
E_s—Contribution of standing horizontal eddies.
E_t—Contribution of transient horizontal eddies.
Q_t—Contribution from realization of potential heat thru vertical sinking.
Ob.—Observed changes.
R—Contribution of radiational processes (a residual).

(1) The upper troposphere over Antarctica is a region of inflowing air which is exhausted in the lowest tropospheric layers; this pattern persists throughout the year, and results in downward vertical motion throughout the troposphere, with the maximum near the 500-mb. level. This corroborates the tropospheric circulation pattern of the model of the Antarctic circulation proposed by Wexler et al. [13] to explain observed Antarctic surface ozone concentrations.

(2) Net inflow and downward vertical motion are the average lower stratospheric conditions, with some downward flow of air from stratosphere to troposphere.

(3) The contribution of large-scale transient horizontal eddies to the heat balance of the Antarctic is about one order of magnitude greater than that of the stationary eddies, with both processes resulting in a net transport of heat into the Antarctic.

(4) The addition of heat to the atmosphere through downward vertical motion is of the same general order of magnitude as the net transport through horizontal eddies. (Our computations indicate that quantitatively the former is 3 to 5 times as large as the latter.)

(5) Both the lower stratosphere and troposphere lose heat through radiational processes throughout the year.

(6) On an annual basis, the net gain of sensible heat through horizontal and vertical motions is one order of magnitude greater than the addition of latent heat to the Antarctic atmosphere through precipitation.

(7) The total radiational heat loss to space annually from the Antarctic atmosphere is on the order of 10^{22} cal. ($\approx$200 ly./day).

(8) During the spring months of October and November, when the greatest warming is observed in the Antarctic stratosphere, the net heat gain of the 75–150-mb. layer both from horizontal advection and vertical motions is greater than in any other 2-month period; radiational processes still result in a net loss of heat from this layer.

7. FURTHER WORK

Similar computations should be carried out for data from other years, in order to permit a comparison of the results obtained using another set of data. Such a program using the data from 1959 is now in progress at the Polar Meteorology Research Project.

The measured cooling rates in table 3 are based only on a limited amount (about 180 ascents) of 1962 radiometersonde data. However, sufficient Antarctic radiometersonde data are now available to permit more reliable estimates of the average winter season cooling rates in the

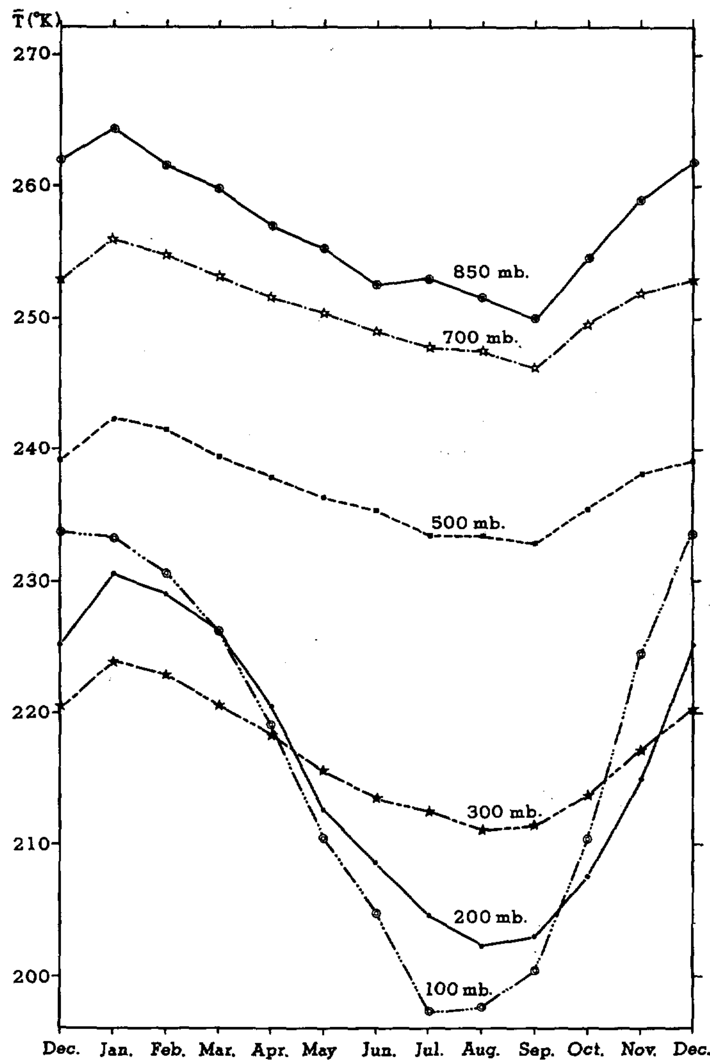

FIGURE 3.—1958 mean monthly temperatures for Antarctic peripheral stations.

various atmospheric layers, and this work is now being carried out. The vertical motions and mean meridional components can then be derived residually from these observed cooling rates and the computed eddy transfers of heat.

The turned wind components, as described by Rubin and Flowers [7], could be computed rather than the true meridional components so as to give the actual transport across the circle of best fit for our stations rather than across a latitude circle of equivalent area but displaced in space. This would remove one possible source of error from our computed $\bar{v}$ components, and refine our computations of those components, the vertical motions, and ultimately the radiational cooling rates. This work is planned for the near future in the Polar Meteorology Research Project.

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APPENDIX

For our calculations we make the following assumptions:

1. Each of our ten stations is representative of the respective one-tenth segment of the circumference of the 72°02′ S. latitude circle in which it is located.

2. Each of the six levels selected is representative of the layer of air containing it as shown below:

850 mb	950–775 mb
700 mb	775–600 mb
500 mb	600–400 mb
300 mb	400–250 mb
200 mb	250–150 mb
100 mb	150– 75 mb

3. There is no net vertical transport of mass or sensible heat through either the 75-mb. level or the 950-mb. level.

4. The only means by which changes in the sensible heat content of the atmosphere within our boundaries can be accomplished are by horizontal eddy transport of sensible heat, by radiative processes, and by changes between potential and sensible heat through mean vertical motion. (On an annual basis for the whole volume, a value is obtained for the latent heat released through precipitation, but this is quite apart from our other computations.)

5. There is no net mass transport across the latitude circle over periods of one month or more (in one month a mean meridional wind component amounting to as little as 1 cm./sec. inflow would result in an average pressure change over the entire area of as much as 22 mb.)

In our computations, we begin by following the general method used by Starr and White [11], that is,

$$(\overline{[Tv]}) = (\overline{[T]}\,\overline{[v]}) + (\overline{[T]'[v]'}) + (\overline{[T]'[v]'}) + (\overline{[T'v']})$$

where T is the air temperature and v the mean meridional wind. The brackets indicate averages around the latitude circle, the superscript bars indicate averages with respect to time (one month), the parentheses indicate averages in the vertical, and the primes signify deviations from the appropriate mean. The total sensible heat flux across our latitude circle for a given period of time can be evaluated. Let us now consider the right hand side of the above equation term by term.

According to our fifth assumption above, $([\overline{v}])$ is zero for periods of a month or more, and the first term vanishes. When computed, $([\overline{v}])$ does not turn out to be zero; accordingly, we follow Obasi [5] in making this term zero by subtracting from $[\overline{v}]$ for each layer the computed $([\overline{v}])$. These adjusted $[\overline{v}]$ values are the ones listed in table 1, and are the values used in our computation of vertical motions.

The third and fourth terms remain invariant with the above adjustment of $[\overline{v}]$ and involve only quasi-horizontal air motions along constant pressure surfaces; the values of net heat gains or losses through these two types of eddy processes can be taken as computed.

The second term of our equation implies vertical motions; Starr and White [11, p. 26] point out that in an atmosphere with an adiabatic lapse rate, the mean cellular flux of potential energy is exactly cancelled by the oppositely directed flux of sensible heat. If we assume that the mean lapse rate of each layer of air within our latitude circle is approximated by the mean layer lapse rate along the periphery, we can estimate the net gain or loss of sensible heat within each layer resulting from the mean cellular circulation, after computing the vertical motions.

The mean vertical motions were computed for each of the five boundary levels separating our six layers, using assumptions 2 and 3 above and the mass conservation law; the total mass transports by such vertical motions were computed as an intermediate step.

Returning to consideration of the layer heat changes resulting from the mean cellular circulation, we make the further assumption that all of the net transport through the lateral boundary of each layer takes place at the datum level of the layer. Consider a gram of air entering a layer at pressure p_1 with temperature T_1, and leaving the layer at some higher pressure p_2 and with temperature T_2 (since it turns out we have only net downward motion to consider). The heat change per gram within the layer from sensible heat transport alone is simply $c_p\ (T_1-T_2)$. The amount of heat added to the layer by each gram of air through conversion of potential to sensible heat by downward vertical motion is $c_p[T_1(p_2/p_1)^{2/7}-T_1]$. Combining the two, the heat added to the layer by the mass m_1 under consideration is equal to

$$m_1 c_p[T_1(p_2/p_1)^{2/7}-T_2],$$

which is the equation used to obtain the sensible heat change resulting from the mean meridional cellular circulation.

Finally, the heat changes for each layer are converted into temperature changes by dividing the total change in heat content over N days by $Nc_p m_L$, where m_L is the total mass of air within the layer.